



Physics at the Fermilab Tevatron Collider

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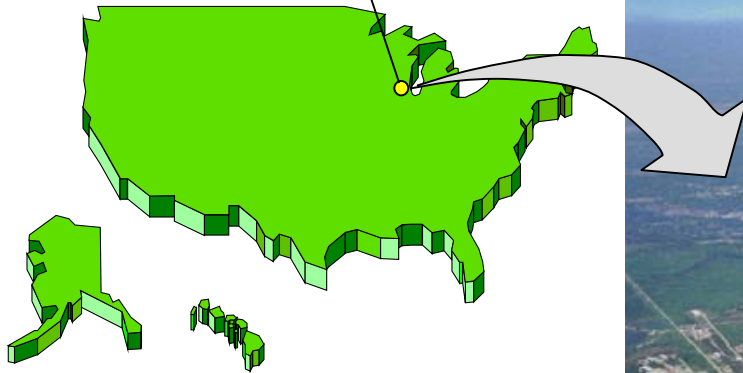
Outline

- **What is the “Tevatron Collider” anyway?**
- **Why do we need one?**
- **What kind of questions are we attempting to answer with it?**
- **How do we do this?**

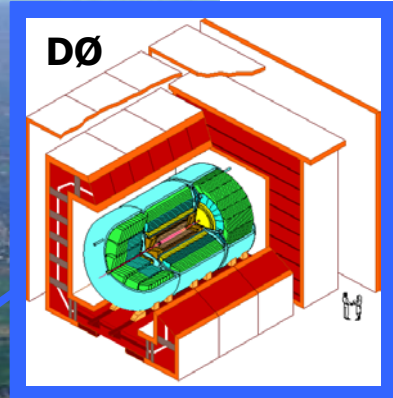
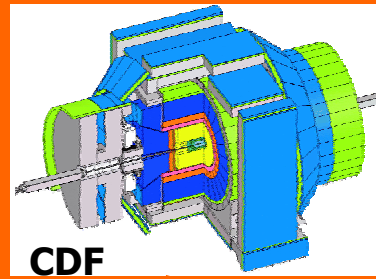


Fermilab

Batavia, Illinois



Chicago



Booster

Tevatron

p

\bar{p}

\bar{p} source

Main Injector
& Recycler

A diagram showing a proton (p) and an antiproton (\bar{p}) colliding. Two blue arrows point towards each other, meeting at a yellow starburst representing the collision point.

$$\sqrt{s} = 1.96 \text{ TeV}$$
$$\Delta t = 396 \text{ ns}$$

Run I 1992-95

Run II 2001-10

100 × larger dataset
at increased energy



What is the universe made of?

- It is often claimed that humans are naturally curious
 - Maybe so, but in my experience they often try to answer this kind of question by sitting and talking and coming up with explanations
 - Call it philosophy, or call it shooting the breeze
- The only reliable way to answer this question is by directly enquiring through experiment
 - not necessarily a “natural human activity”, but perhaps the greatest human invention
 - Something that is not understood, and therefore not particularly liked, by many people
 - often tolerated mainly because it is useful
- Something to think about, especially when we are trying to explain scientific projects that are not, a priori, useful



Experiment has taught us:

- **Complex structures in the universe are made by combining simple objects in different ways**
 - **Periodic Table**
- **Apparently diverse phenomena are often different manifestations of the same underlying physics**
 - **Orbits of planets and apples falling from trees**
- **Almost everything is made of small objects that like to stick together**
 - **Particles and Forces**
- **Everyday intuition is not necessarily a good guide**
 - **We live in a quantum world, even if it's not obvious to us**



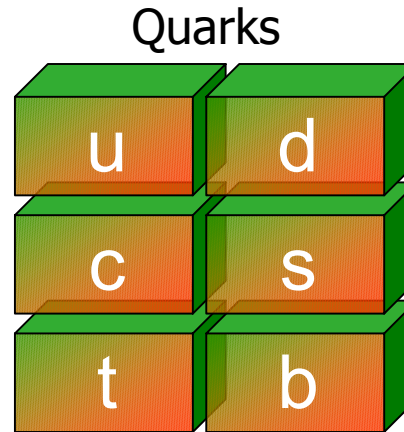
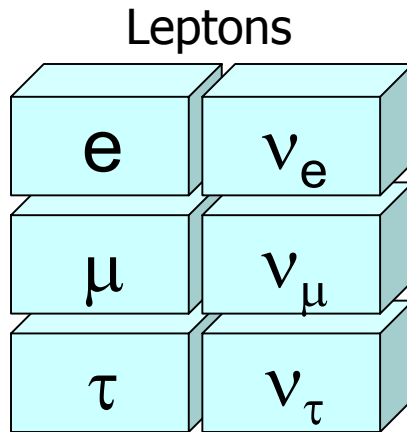
Particles and Forces Timeline

- **1897-1920's**
 - The electron (vacuum tubes)
 - Atomic physics, X-rays, quantum mechanics
- **1930's**
 - The nucleus (Rutherford's experiment)
- **1940's**
 - Nuclear physics
- **1950's**
 - Particle physics (explosion of mesons and baryons)
 - Quantum Field Theory (Feynman et al.)
- **1960's – 1970's**
 - Quarks and leptons
- **1980's**
 - Electroweak Unification, W and Z bosons
- **1990's**
 - Consolidation of the Standard Model, top quark
 - Increasing interest in "Quarks to the Cosmos"



"Standard Model" of Particles and Forces

- Point like, spin- $1/2$ fermionic constituents



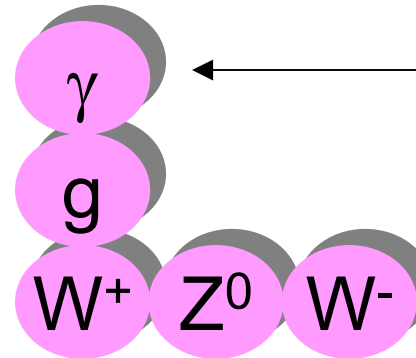
- Which interact by exchanging spin-1 vector bosons

Electromagnetic 10^{-2}

Strong 1

Weak 10^{-6}

Gravity 10^{-40}



Higgs

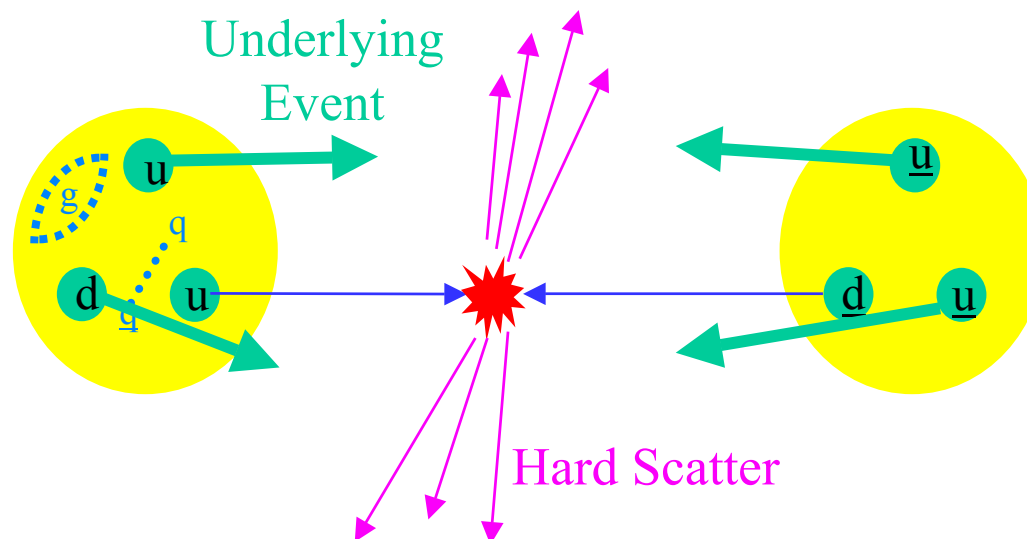
We'll come back to this guy later

Relative strengths

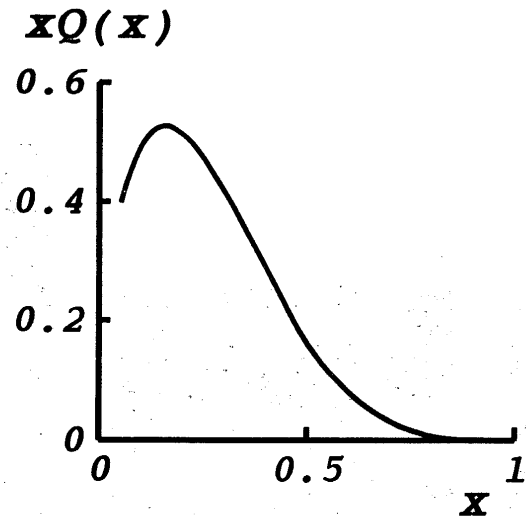


Particle Accelerators

- Accelerators allow us to explore the interactions of particles at high energies
 - See the underlying physics not the dressing
- We can collide beams of either electrons or protons
 - Because electron beams radiate when accelerated, proton accelerators are the best way to reach very high energies (electron accelerators play an important complementary role)
- Proton-antiproton collision:



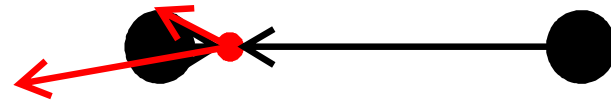
Proton-Antiproton Collisions



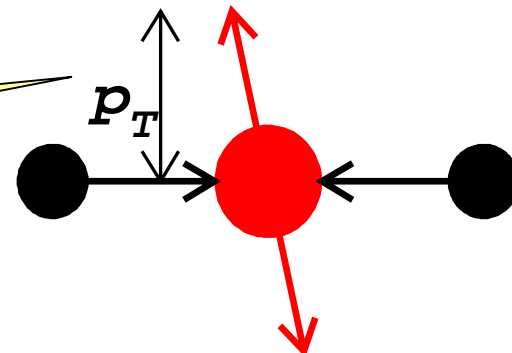
For every proton there is a probability for a single quark (or gluon) to carry a fraction " x " of the proton momentum

A good way to tell that a hard (and therefore interesting) collision occurred. Forms the basis of on-line event selection ("triggering")

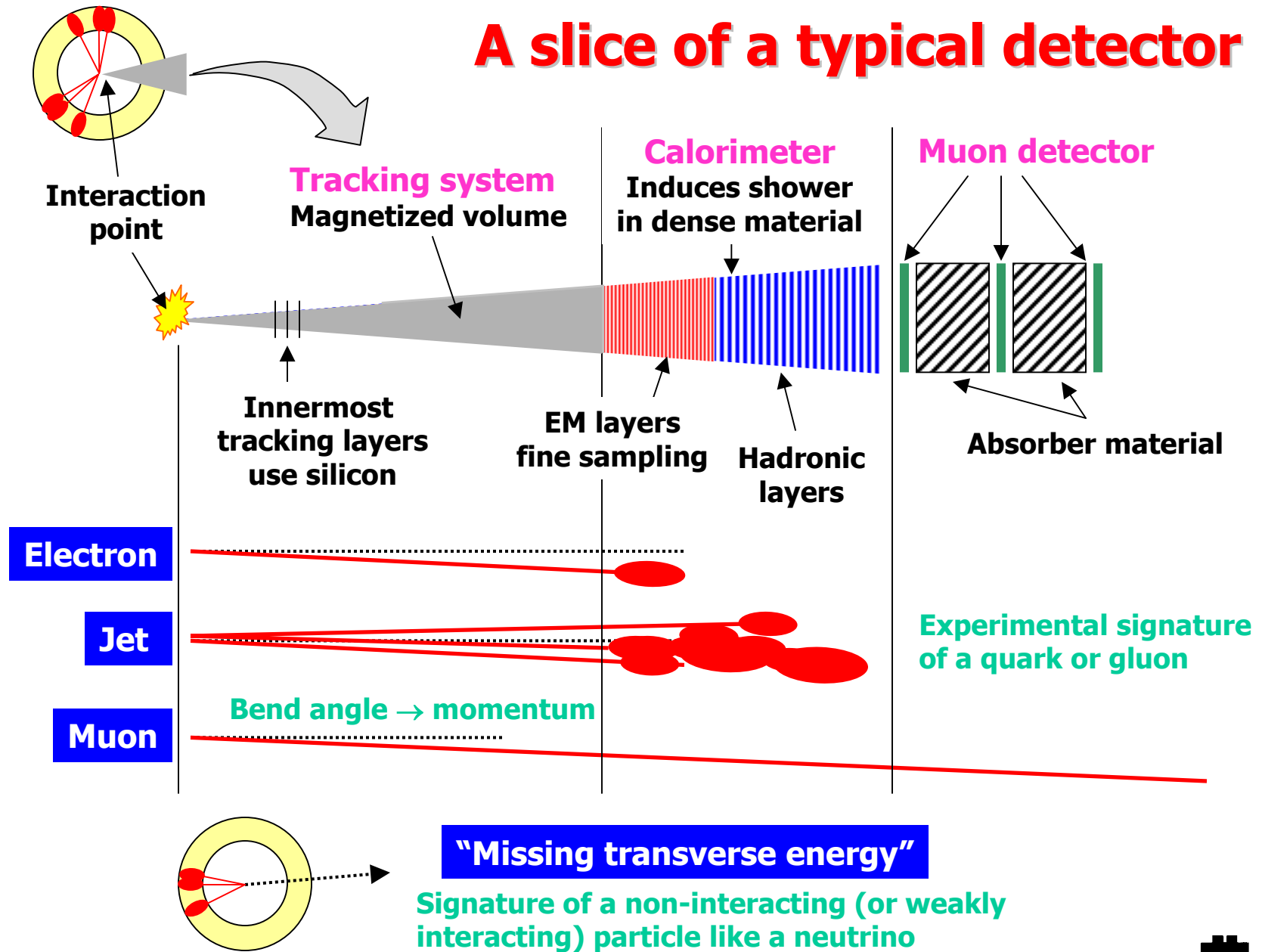
Small x = small energy, products boosted along beam direction

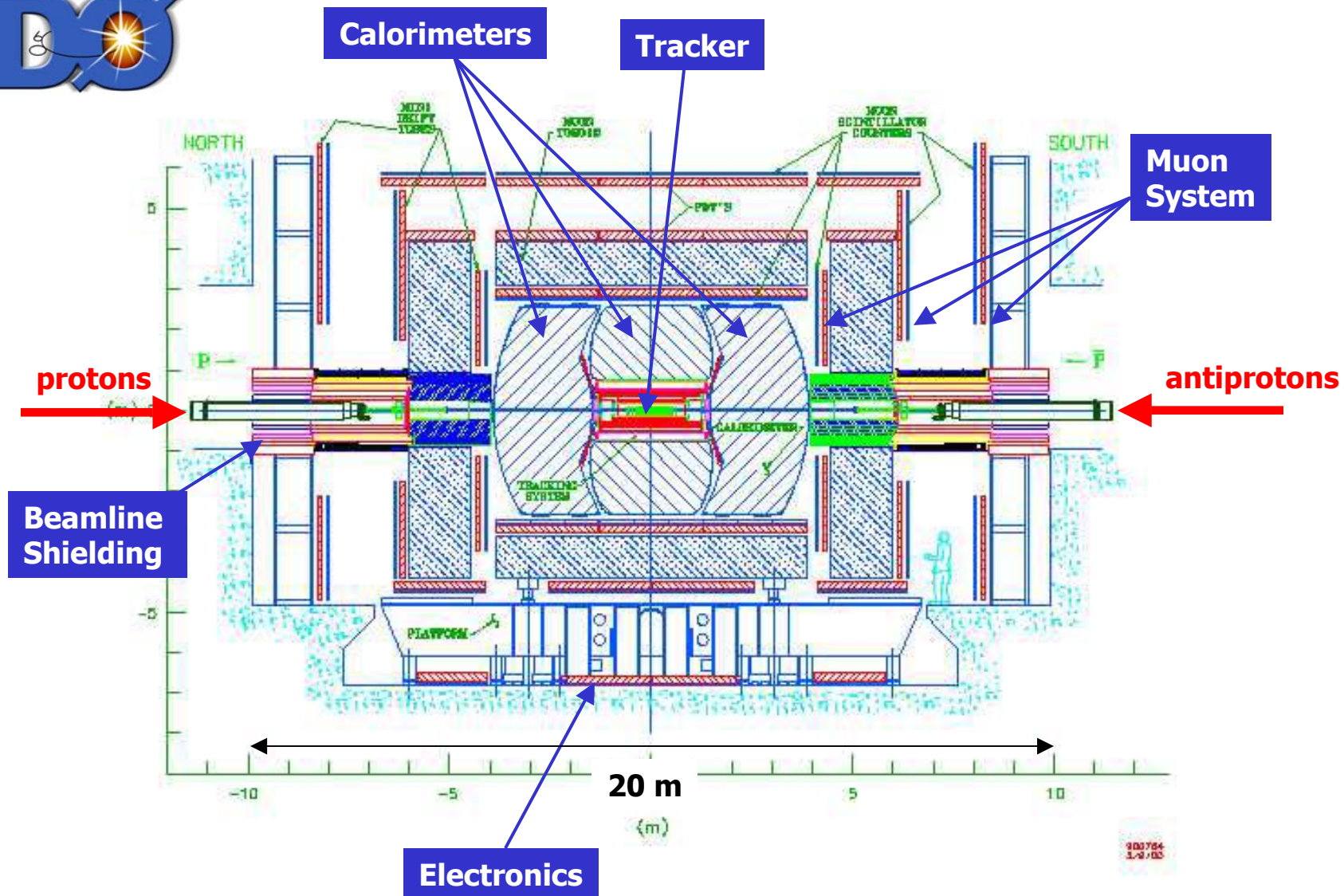


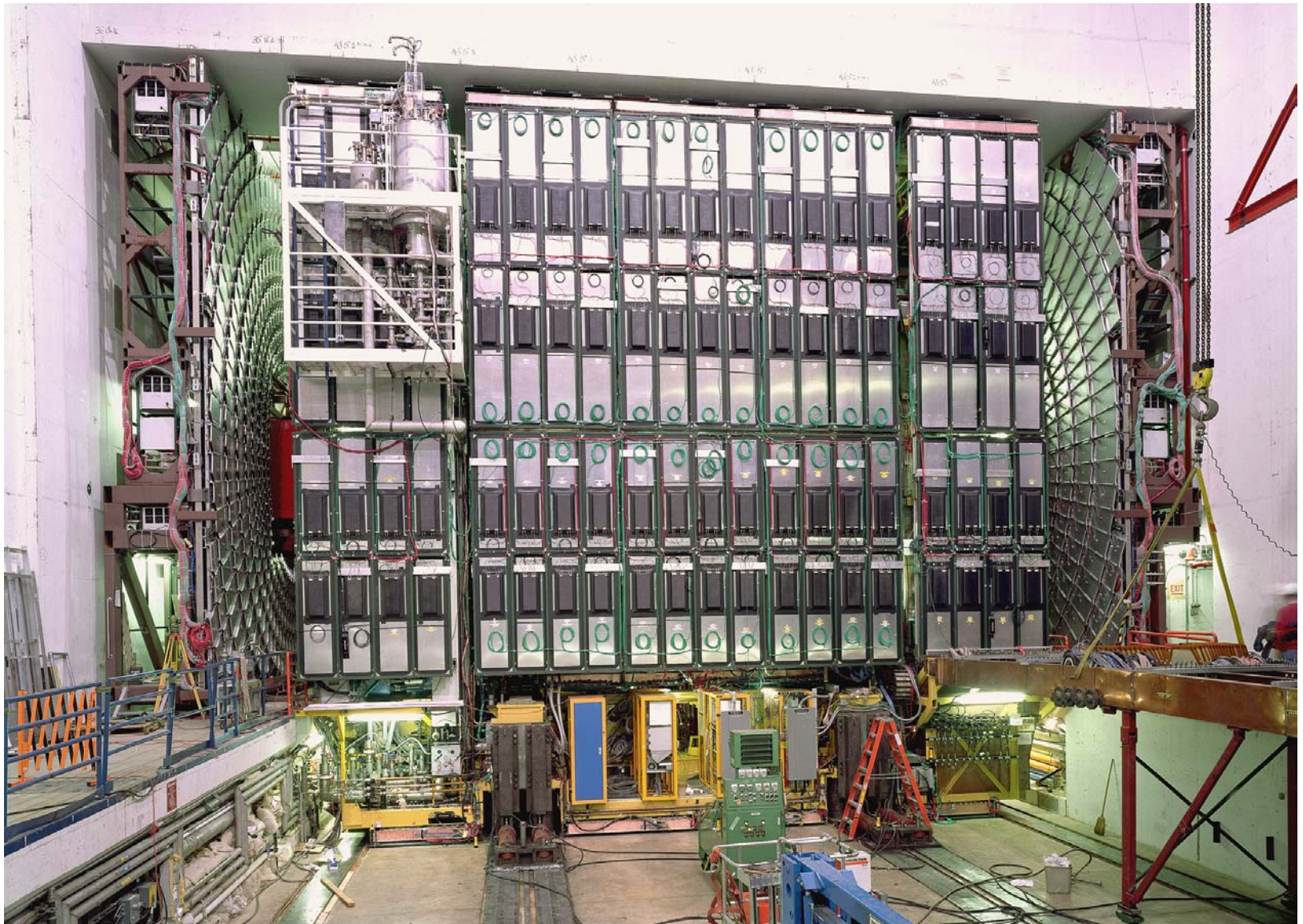
Large x = large energy, can create massive objects whose decay products have a large momentum transverse to the beam



A slice of a typical detector

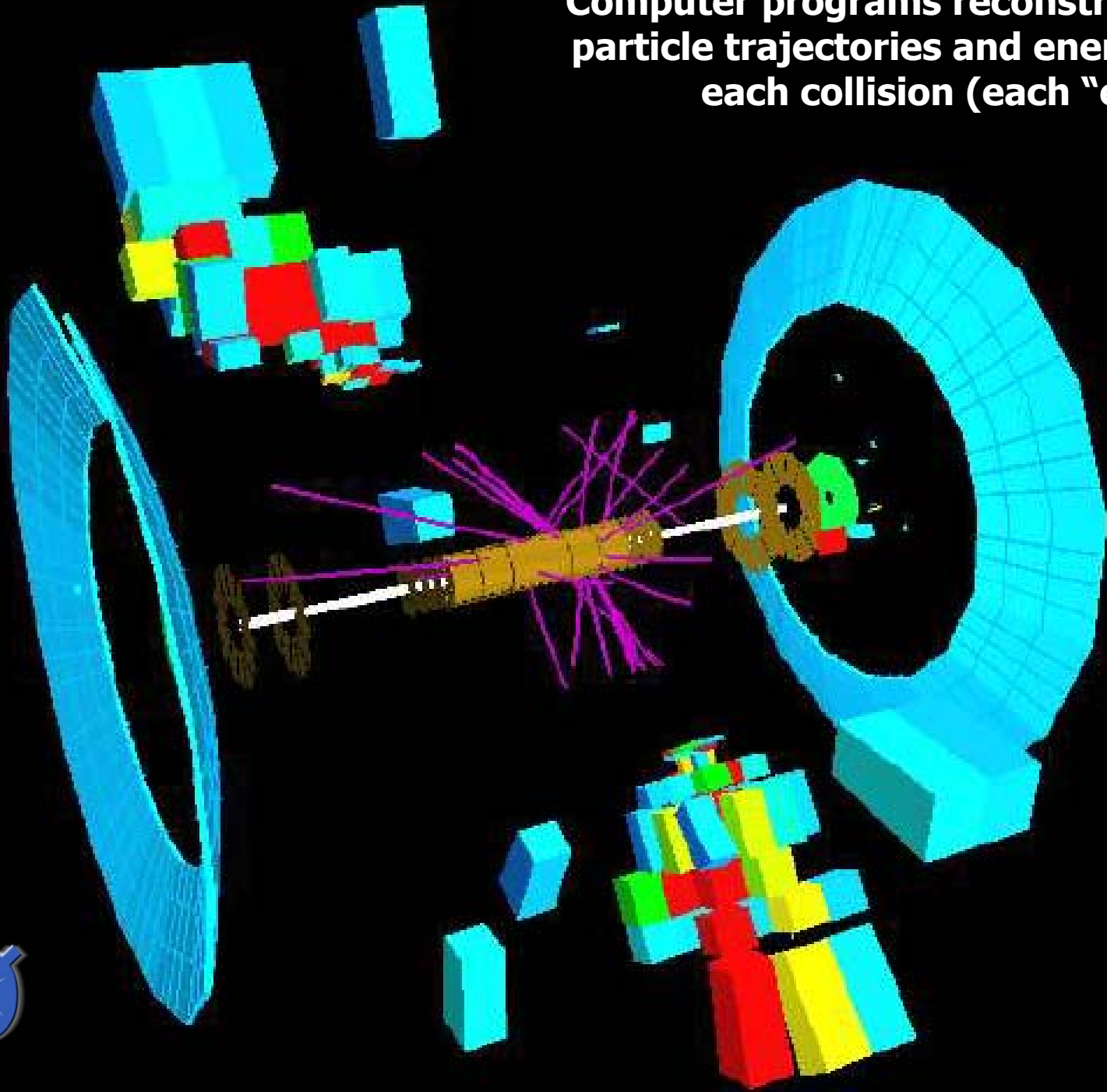






DØ detector installed in the Collision Hall, January 2001

Computer programs reconstruct the particle trajectories and energies in each collision (each “event”)



The work of many people...

The DØ detector
was built and is
operated by an
international
collaboration
of ~ 550 physicists
from 18 nations

> 50% non-USA
~ 120 graduate
students



What do physicists actually do?

- Design and build hardware
 - Detectors, electronics
- Write software
- Operate the detector
- Interpret data
- Present, refine, discuss our results among ourselves
- Publish papers



Remote International Monitoring for the DØ Experiment

Detector Monitoring data sent
in real time over the internet

9 am

NIKHEF
Amsterdam

2 am

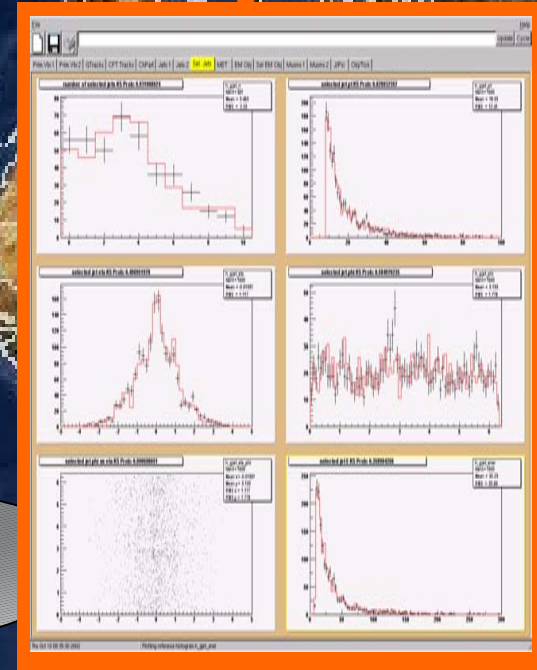
Fermilab

DØ physicists in Europe
use the internet and
monitoring programs to
examine collider data in real
time and to evaluate
detector performance and
data quality.

They use web tools to
report this information back
to their colleagues at
Fermilab.



DØ detector



The online monitoring project has been developed by DØ physicists and is coordinated by Dr. Pushpa Bhat from Fermilab. Jason Webb, a DeVry University, Chicago, undergraduate student is helping develop and maintain the interactive tools for the remote physicists.

What next?

- You've got this great standard model and you know all about all of the particles and forces involved. So why do you need to do these experiments? Isn't it all done?
- Yes, we know a lot, but we know a lot less than we would like, and we know enough now to ask some deeper questions
 - the paradox of the “circumference of knowledge”



Deeper Questions

Not just “what happens?” type of questions — “why does it happen?”

For example

- Why are some forces weak and others strong?
- What is the dark matter that seems to be responsible for cosmic structure?
- What is the structure of spacetime?

Not purely particle physics questions any more
Particle physics is the DNA of the universe



Q:

- **Why are some forces weak and others strong?**
 - **Is the Universe filled with an energy field?**
 - **Is there a unification of forces at very high energies?** *(We'll come back to this later in the talk)*



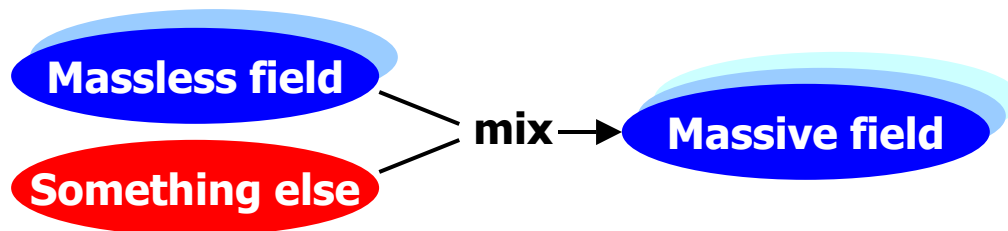
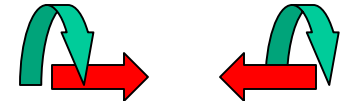
Electroweak Symmetry Breaking

- Photons and W/Z bosons couple to particles with the same strength
 - Electroweak unification
- Yet while the universe (and this room) is filled with photons, W's and Z's mediate a weak force that occurs inside nuclei in radioactive beta decay
 - This is because the W and Z are massive particles
 - The unification is “broken”
- Where does this mass (the symmetry breaking) come from?
 - Not like the mass of the proton, which is the binding energy of its constituents
- In the Standard Model, the W and Z get their mass because the universe is filled with an energy field, called the Higgs field, with which they interact (and in fact mix)
 - The universe is a refractive medium for W's and Z's

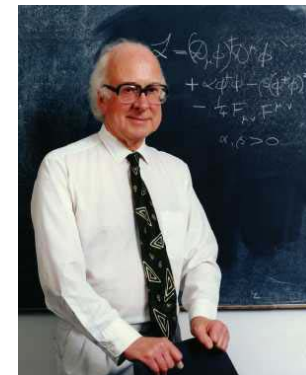


What does mass mean?

- For an elementary pointlike particle
 - propagates through the vacuum at $v < c$
 - Lorentz transform mixes LH and RH helicity states: symmetry is broken
 - mass is equivalent to an interaction with the (Quantum Mechanical) vacuum (a “refractive index”)
 - coupling strength = mass
- For a spin-1 state like a photon, there is an extra effect
 - massless \rightarrow two polarization states
 - massive \rightarrow three polarization states
 - where does this additional degree of freedom come from?



The “Higgs Mechanism”



The Higgs Mechanism

- Hence, in the Standard Model
(Glashow, Weinberg, Salam, 't Hooft, Veltmann)
 - “electroweak symmetry breaking” through introduction of a scalar field which permeates all of space with a finite vacuum expectation value
 - Cosmological implications!
 - How can we relate this with “Dark Energy?”
 - If the same field couples to fermions → generates fermion masses
- An appealing picture: is it correct?
 - One clear and testable prediction: there exists a **neutral scalar particle** which is an excitation of the Higgs field

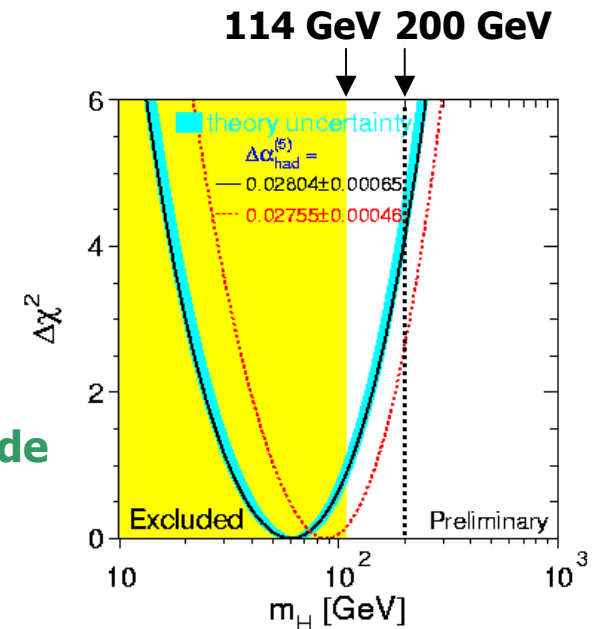
We want to excite this field in the lab and study its quanta!
“Pluck the violin-string of the universe”

- All its properties (production and decay rates, couplings) are fixed within the SM, except for its own mass



Searching for the Higgs

- In the last decade, the focus was on experiments at the LEP e^+e^- collider at CERN (European Laboratory for Particle Physics)
 - precision measurements of parameters of the W and Z bosons, combined with Fermilab's top quark mass measurements, set an upper limit of $m_H \sim 200$ GeV
 - direct searches for Higgs production exclude $m_H < 114$ GeV
- Summer and Autumn 2000: Hints of a Higgs
 - the LEP data may be giving some indication of a Higgs with mass 115 GeV (right at the limit of sensitivity)
 - despite these hints, CERN management decided to shut off LEP operations in order to start construction on the Large Hadron Collider (a new accelerator with seven times the energy of the Tevatron)
- Until the end of the decade, Fermilab has a unique opportunity to discover or exclude this object





THE HIGGS BOSON

1964
Peter Higgs suggested introducing a new field (the Higgs Boson) in order to explain the origin of the mass of elementary particles. This is the most widely accepted scenario.

A famous particle acquires a mass through interactions with people at a party (Higgs field).

A rumour at a party spreads.

The Higgs boson is the only missing ingredient of the Standard Model.

2008
This scenario is expected to be tested by the Higgs boson at the LHC.


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Optic Nerve Higgs-Bozon Multi-Lens System

Sale Price: ~~\$51.99~~ **\$25.98** (That's 50% Off!)**Item #20-1379C****In Stock**

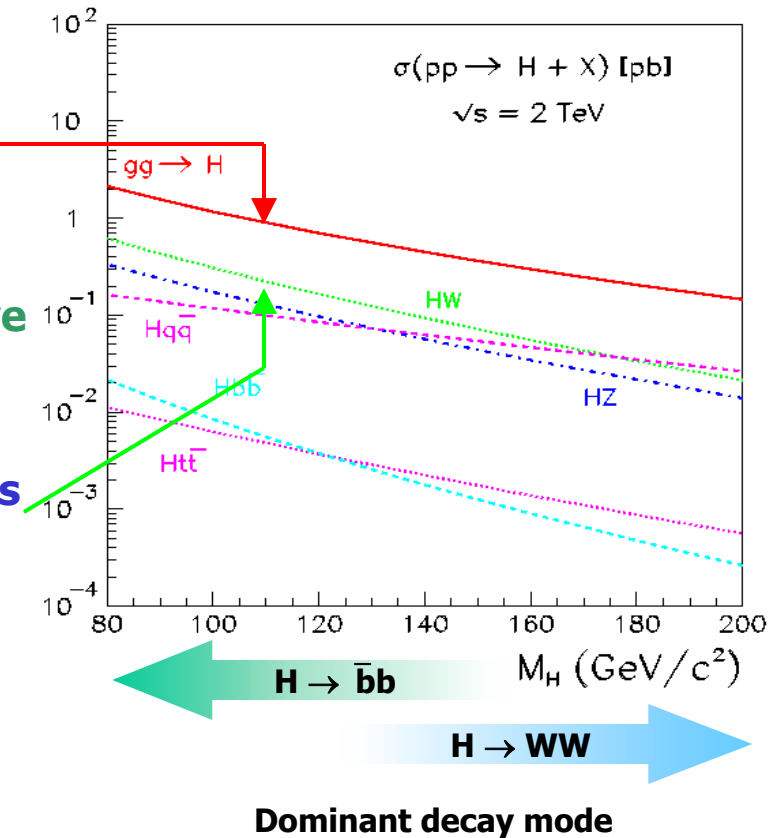
Finely tuned optics provide incredible clarity, and the interchangeable lens system makes you ready for any condition. Tough, light Grilamid nylon frame, grade-A polycarbonate lenses tuned with FocalPoint lens technology. Vented lenses keep fogging to a minimum. Brown, Clear, Orange lenses all block 100% UV radiation. Frame colors: Blue (BLU), Black (BLK), Carbon (CAR), Silver (SIL), Green (GRN), Gun (GUN).

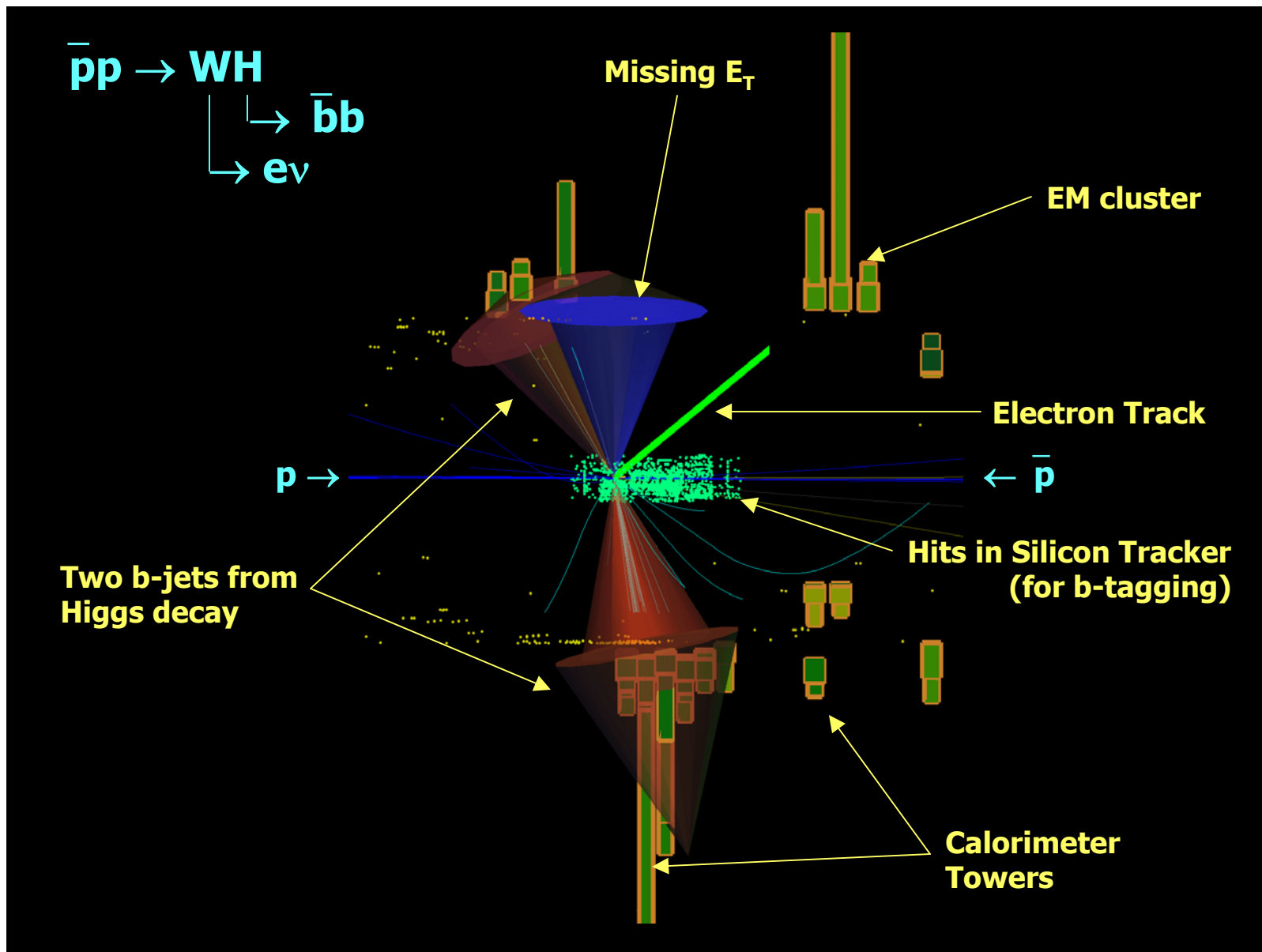
Ready to buy?**Pick:**

...then

Higgs Hunting at the Tevatron

- For any given Higgs mass, the production cross section and decays are all calculable within the Standard Model
- Inclusive Higgs cross section is quite high: $\sim 1\text{pb}$
 - for masses below $\sim 140\text{ GeV}$, the dominant decay is $H \rightarrow b\bar{b}$ which is swamped by background
 - at higher masses, can use inclusive production plus WW decays
- The best bet below $\sim 140\text{ GeV}$ appears to be associated production of H plus a W or Z
 - leptonic decays of W/Z help give the needed background rejection
 - cross section $\sim 0.2\text{ pb}$





Example: $m_H = 115 \text{ GeV}$

- $\sim 2 \text{ fb}^{-1}/\text{expt}$ (2004): exclude at 95% CL
- $\sim 5 \text{ fb}^{-1}/\text{expt}$ (2006): evidence at 3σ level
- $\sim 15 \text{ fb}^{-1}/\text{expt}$ (2010): expect a 5σ signal

Every factor of
two in luminosity
yields a lot
more physics

- Events in one experiment with 15 fb^{-1} :

Mode	Signal	Background	S/\sqrt{B}
1 ν bb	92	450	4.3
ν ν bb	90	880	3.0
1 1 bb	10	44	1.5

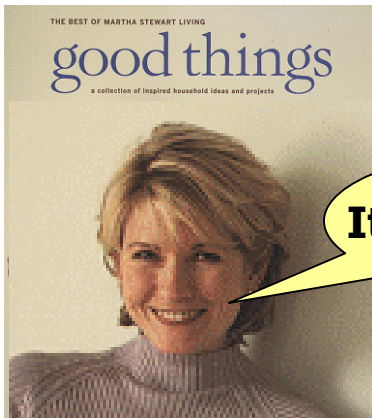
- If we do see something, we will want to test whether it is really a Higgs by measuring:
 - mass
 - production cross section
 - Can we see $H \rightarrow WW$? (Branching Ratio $\sim 9\%$)
 - Can we see $H \rightarrow \tau\tau$? (Branching Ratio $\sim 8\%$)



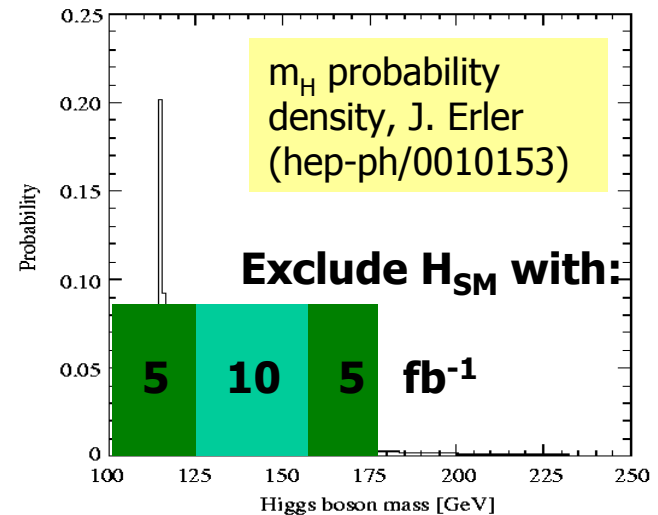
What if we see nothing?

As long as we have adequate sensitivity, exclusion of a Higgs would itself be a very important discovery for the Tevatron

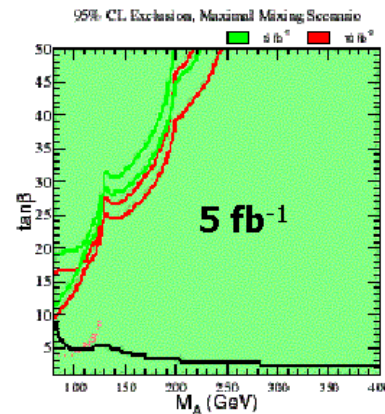
- In the SM, can exclude most of the allowed mass range
- If supersymmetry (SUSY) is correct, we can potentially exclude all the remaining parameter space
- Would certainly make life “interesting” for the theorists



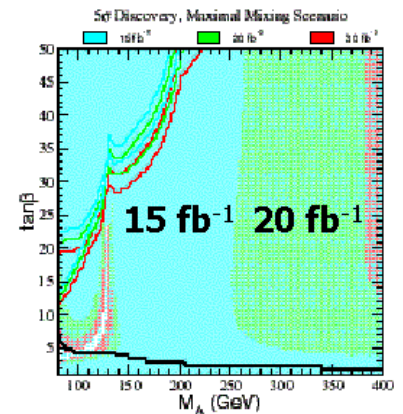
It's a good thing



95% exclusion



5 σ discovery



Exclusion and discovery for SUSY Higgs sector, maximal stop mixing, sparticle masses = 1 TeV

Q:

- **What is the dark matter that seems to be responsible for structure in the universe?**
 - **Is it a new kind of particle?**
 - **Does this point to a previously undiscovered symmetry of the universe?**



Mass shapes the Universe

...through gravitation, the only force that is important over astronomical distances

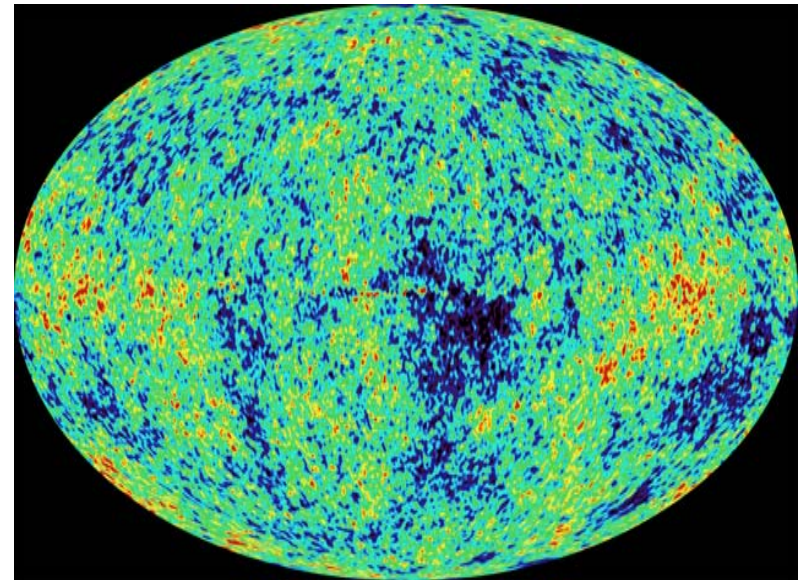
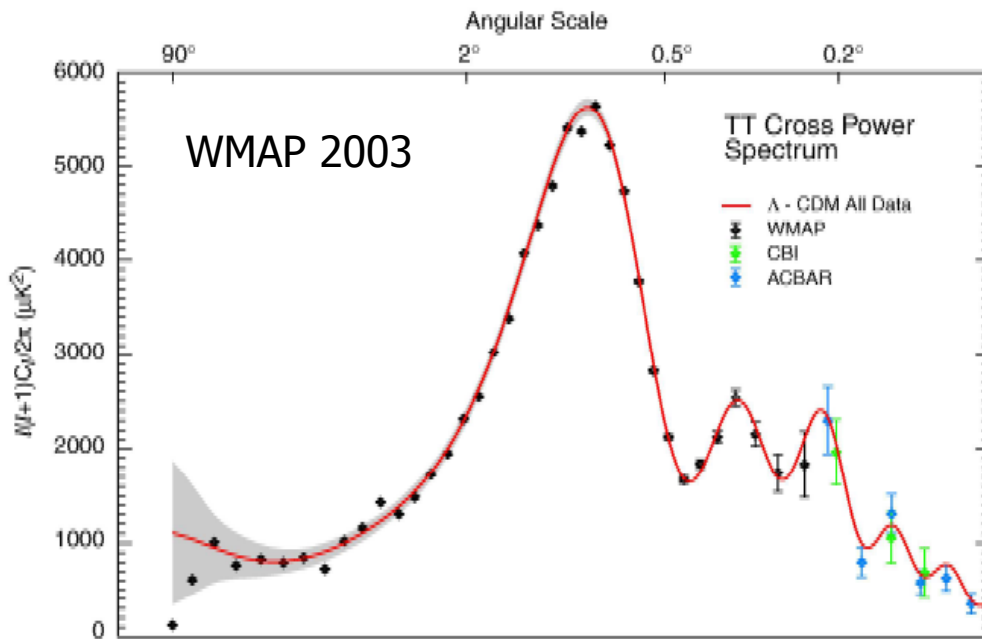
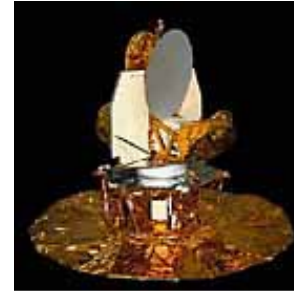


- **Masses of Atoms**
 - binding energies from the strong force (QCD)
- **Dark Matter**
 - Long known that dynamical mass much greater than visible luminous material
 - Primordial nucleosynthesis, D/He abundance measures baryon density



Cosmic Microwave Background

- Recent measurements of “acoustic peaks” vs. multipole number



What is Dark Matter?

Compare with cosmological models

- Size of DM “potential wells” into which matter fell
 - Allows matter and DM densities to be extracted
- About six to seven times more mass ($27 \pm 4\%$) than there is baryonic matter ($4.4 \pm 0.4\%$)
- new particles?
 - Weakly interacting, massive relics from the very early universe
-
- Two experimental approaches:
 - Search for dark matter particles impinging on earth
 - Try to create such particles in our accelerators



Supersymmetry

- **Postulate a symmetry between bosons and fermions:**
 - all the presently observed particles have new, more massive superpartners (SUSY is a broken symmetry)
- **Theoretically nice:**
 - additional particles cancel divergences in the Higgs mass
 - solves a deficiency of the SM
 - closely approximates the standard model at low energies
 - allows unification of forces at much higher energies
 - provides a path to the incorporation of gravity and string theory:
Local Supersymmetry = Supergravity
- **Predicts multiple Higgs bosons, strongly interacting squarks and gluinos, and electroweakly interacting sleptons, charginos and neutralinos**
 - masses depend on unknown parameters,
but expected to be 100 GeV - 1 TeV

**Lightest neutralino is a good explanation for cosmic dark matter
Potentially discoverable at the Tevatron**



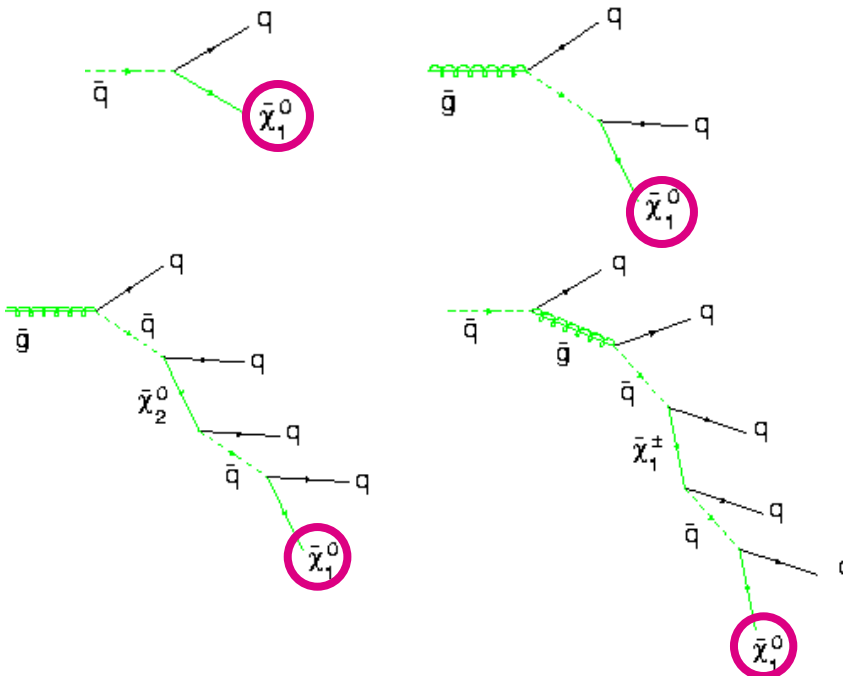
Supersymmetry signatures

- Squarks and gluinos are the most copiously produced SUSY particles
- As long as R-parity is conserved, cannot decay to normal particles
 - missing transverse energy from escaping neutralinos (lightest supersymmetric particle or LSP)

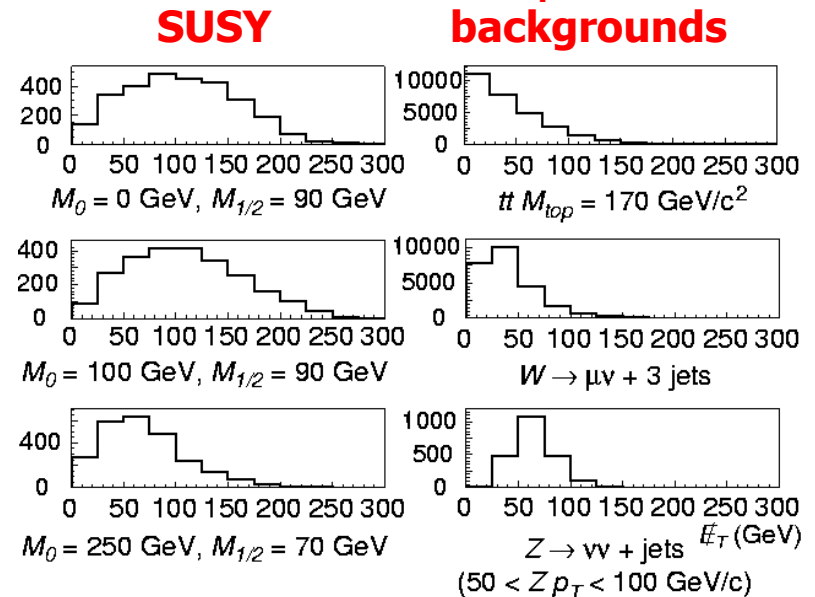
Make dark matter at the Tevatron!

Detect its escape from the detector

Possible decay chains always end in the LSP



**Missing E_T
backgrounds**

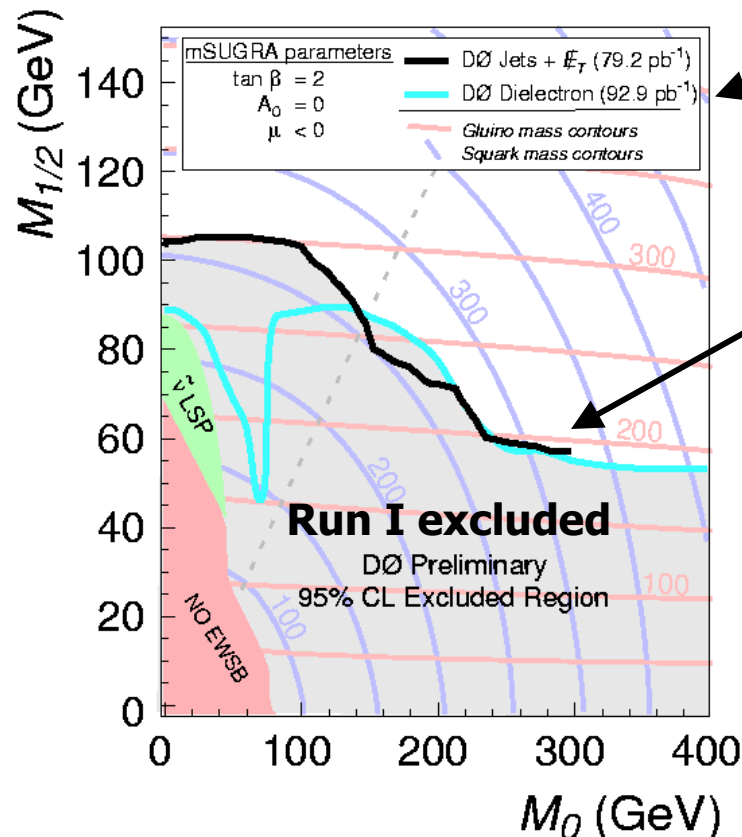


Search region typically $> 75 \text{ GeV}$



Search for squarks and gluinos

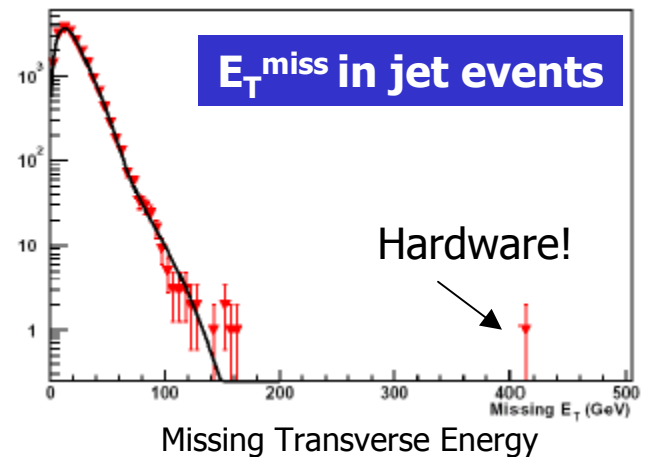
- Two complementary searches
 - jets plus missing E_T and no electrons/muons
 - 2 electrons, 2 jets + Missing E_T



Reach with 2 fb^{-1} :
gluino mass ~ 400 GeV

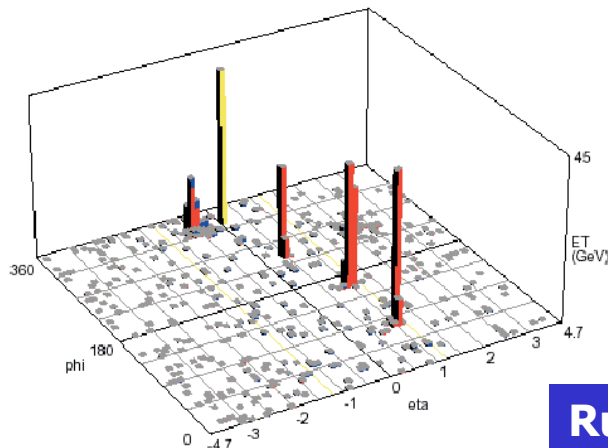
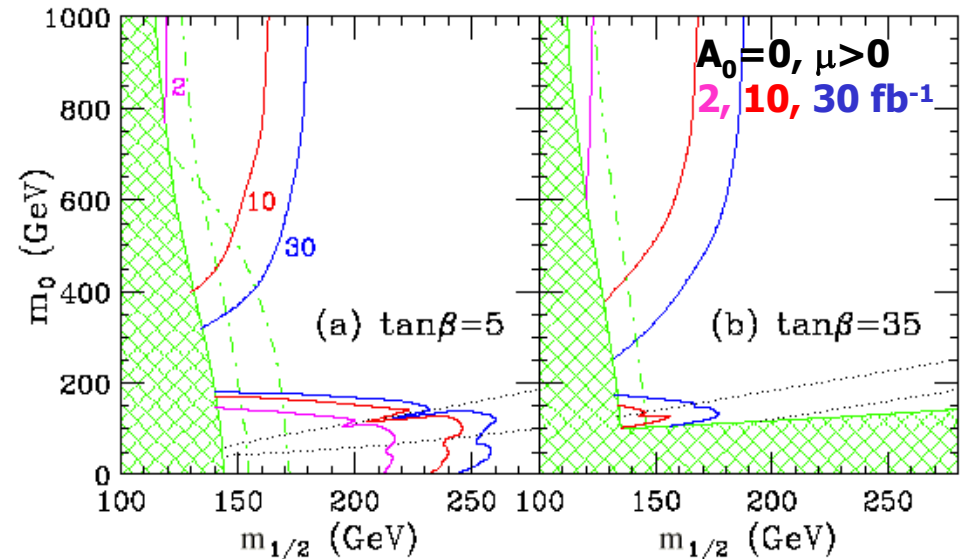
Run I (1992-95)
gluino ~ 200 GeV
squark ~ 250 GeV

Run II analysis has begun:



Chargino/neutralino production

- “Golden” signature
 - Three leptons
 - very low standard model backgrounds
- This channel becomes increasingly important as squark/gluino production reaches its kinematic limits (masses $\sim 400\text{-}500\text{ GeV}$)
- Reach on χ^\pm mass
 - $\sim 180\text{ GeV}$ ($\tan\beta = 2, \mu < 0$)
 - $\sim 150\text{ GeV}$ (large $\tan\beta$)



Searches have begun!
So far number of events is consistent with expectations — we need a lot more data, but the tools are in place

Run II Trilepton candidate



Q:

- **What is the structure of spacetime?**
 - **How many dimensions are there?**
 - **Is geometry the way to connect gravity to the other forces?**



Connections with Gravity

- While supersymmetry is required for supergravity, it was usually assumed that any unification of forces would occur at the Planck scale $\sim 10^{19}$ GeV
 - very large hierarchy between the electroweak scale and gravitational scales
- Powerful new idea:
Gravity may propagate in extra dimensions, while the gauge particles and fermions (i.e. us) remain trapped in 3+1 dimensional spacetime
 - extra dimensions not necessarily small in size (millimeters!)
 - true Planck scale may be as low as the electroweak scale
 - Gravity could start to play a role in experiments at \sim TeV
- Many different theoretical ideas, with different topologies possible
 - large extra dimensions (ADD)
 - TeV scale extra dimensions
 - warped extra dimension (RS)



A Far-Out Theory Describing What's Out There

Physicists have long sought a unified theory to explain all the forces and matter in the universe. Superstring theory is an attempt at such a unification, and now "brane" theory expands on it, proposing that our universe is one of many membranes that "float" in a multidimensional megaverse.

SUPERSTRING THEORY

At its most basic level, the universe consists of tiny loops of string that vibrate at different frequencies.



Since matter can be described in terms of energy, each frequency (energy) corresponds to a type of particle (matter) just as different frequencies coming from a violin's strings produce different notes.

STRING SIZE
The strings are to an atom...



...as an atom is to the solar system.

Brane Theory

It expands superstring theory to include vibrating membranes, or branes, which may have many dimensions.

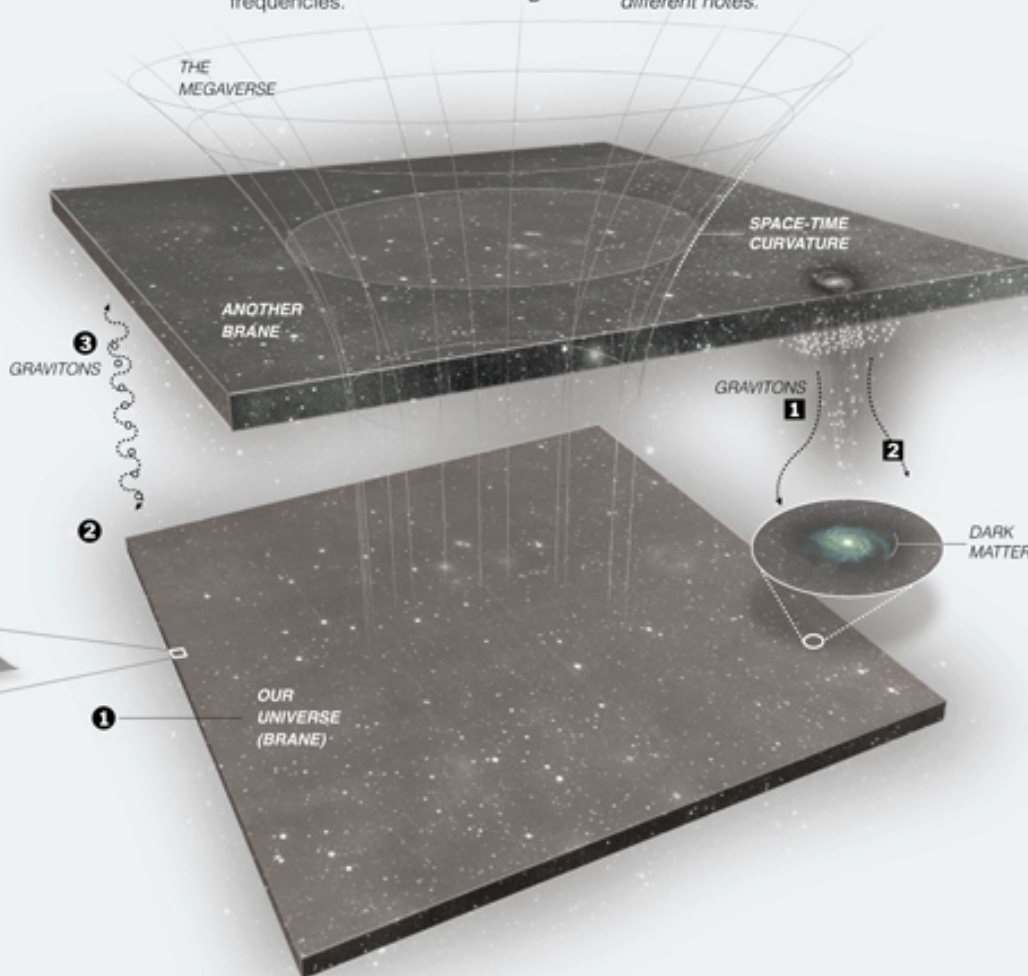
1 Our universe can be thought of as a three-dimensional brane floating inside a four-dimensional megaverse.

2 Most strings that compose our universe are attached to the brane's surface, and so most particles that exist on our brane are confined to its three-dimensional space.



3 However, the particles that convey gravity, gravitons, are not tightly confined to any particular brane, and some of them roam across to other branes in the megaverse.

Sources: "Q is for Quantum," by John Gribbin;
"The Ideas of Particle Physics," by J.E. Dodd



BRANE THEORY AND GRAVITY

Gravity is described by relativity theory as curved space-time, and it is the weakest of the forces in our universe. Brane theory contains a possible explanation.

1 Gravitons, conveyors of gravity, may be concentrated on a different brane where the space-time of the megaverse is severely curved. Only a small number of gravitons make their way here, so gravity is felt as a weak force.

DARK MATTER

Cosmologists suggest that it makes up 90 percent of our universe. It neither emits or absorbs light, but it exerts gravity. According to brane theory, it may just be ordinary matter concentrated on other branes, and its light cannot shine through to this universe.

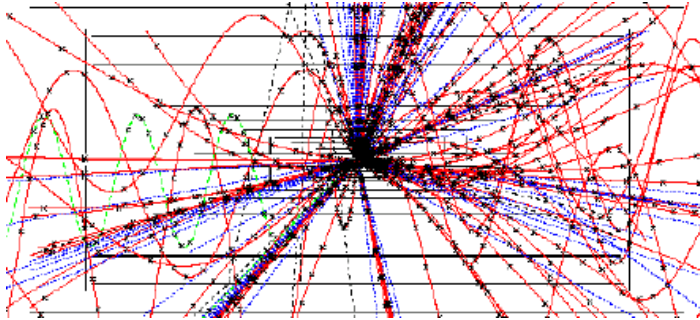
2 The light from dark matter, conveyed by particles called photons, would cling to the surface of the foreign brane, but gravitons might seep across the divide. Pulled by our galaxies' local gravitational force, the gravitons would cluster into halos around the galaxies.

Steve Duenes/The New York Times



TeV-scale gravity

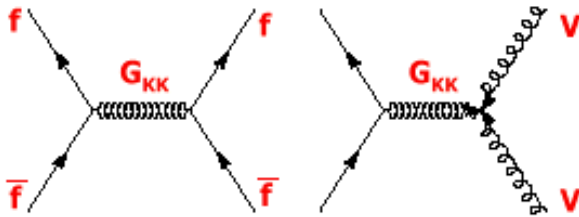
- Observable effects can be direct and spectacular . . .



Production of Black Holes may even occur

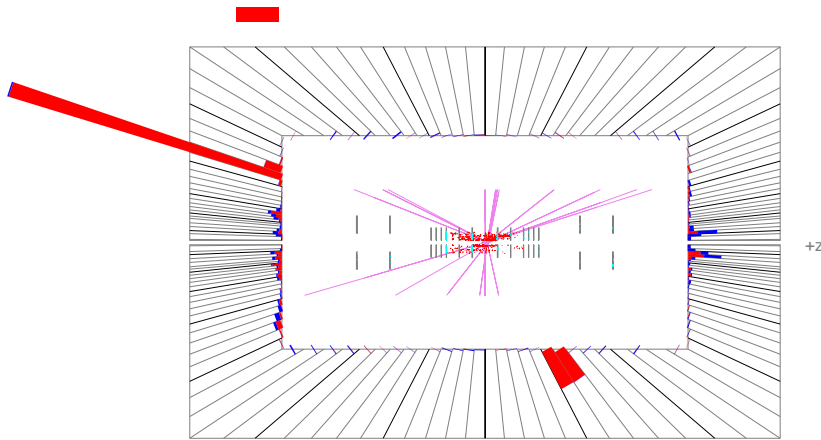
Decay extremely rapidly (Hawking radiation)
with spectacular signatures

- Or indirect . . .
 - Virtual graviton exchange can enhance the production rate for e^+e^- and $\gamma\gamma$ pairs with large masses and angle relative to the beamline



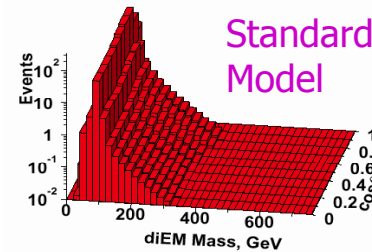
Searching for Extra Dimensions

- We have started this analysis with Run II data

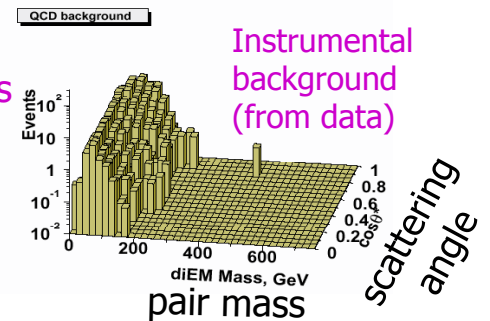
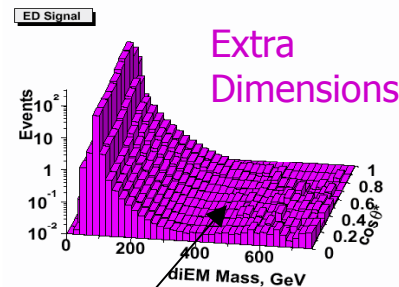
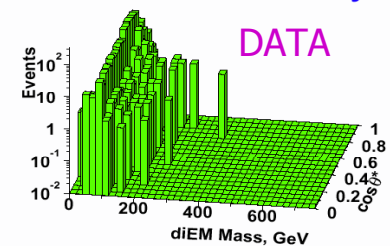


High-mass electron pair event

$\bar{p}p \rightarrow ee$ and $\gamma\gamma$



DØ Run 2 Preliminary



Signal is an excess of events at large mass and large angle

First Run II limits from $\bar{p}p \rightarrow ee, \mu\mu, \gamma\gamma$ (summer 2002)

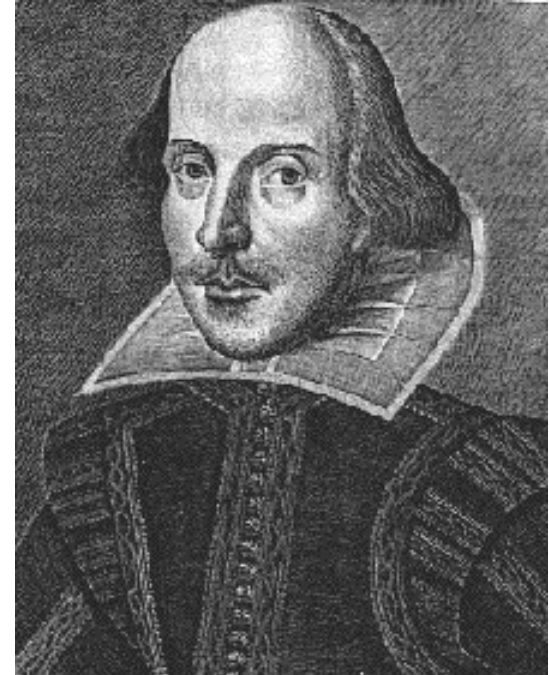
$M_S(\text{GRW}) > 0.92 \text{ TeV (ee/}\gamma\gamma\text{)}$

$M_S(\text{GRW}) > 0.50 \text{ TeV } (\mu\mu)$



Are we asking the right questions?

*There are more things in heaven
and earth, Horatio,
Than are dreamt of in your
philosophy. — W.S.*



- **We need a way to search for new phenomena that is not constrained by our preconceptions of what might be “out there.”**





Sleuth

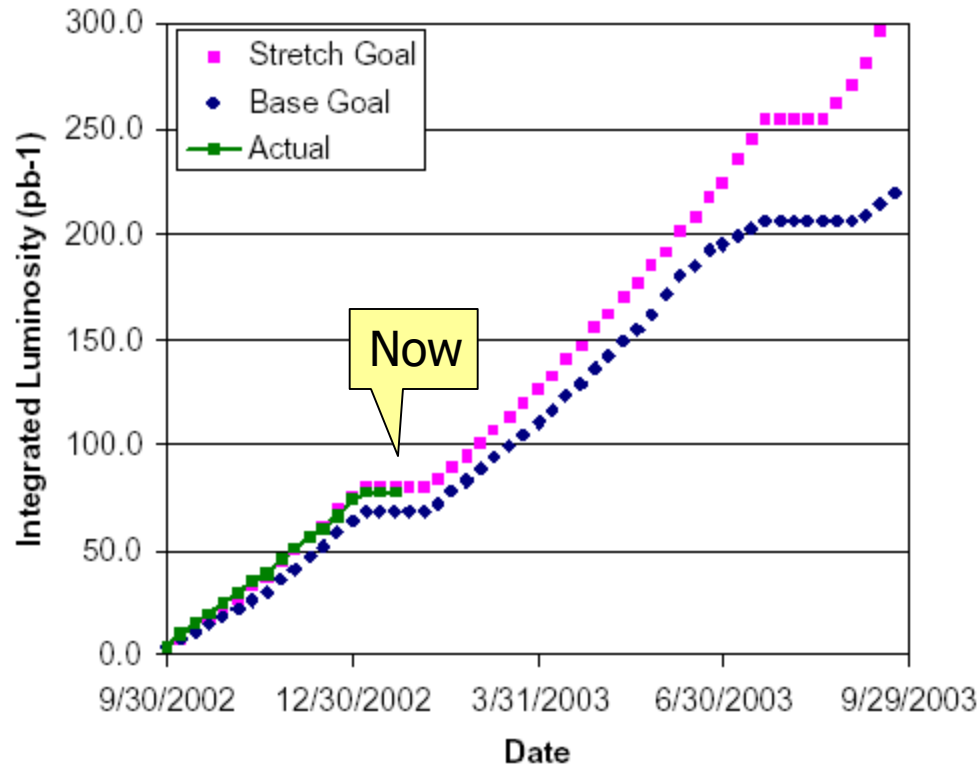


- A new approach from DØ: attempt at a model-independent analysis framework to search for new physics
 - will never be as sensitive to a particular model as a targeted search, but open to anything
 - searches for deviations from standard model predictions
- Systematic study of 32 final states involving electrons, muons, photons, W's, Z's, jets and missing E_T in the DØ 1992-95 data
- Only two channels with some hint of disagreement
 - 2 electrons + 4 jets
 - observe 3, expect 0.6 ± 0.2 , CL = 0.04
 - 2 electrons + 4 jets + Missing E_T
 - observe 1, expect 0.06 ± 0.03 , CL = 0.06
- While interesting, these events are not an indication of new physics, given the large number of channels searched
 - 89% probability of agreement with the Standard Model (alas!)

This approach will be extremely powerful in future!



Prospects for 2003



- **Department of Energy Review Committee, October 2002:**
 - ... Fermilab has embraced the challenge of meeting the luminosity goals for the Tevatron complex...
 - ... there is a good likelihood that the “base” luminosity goal set for FY03 will be met or even exceeded.

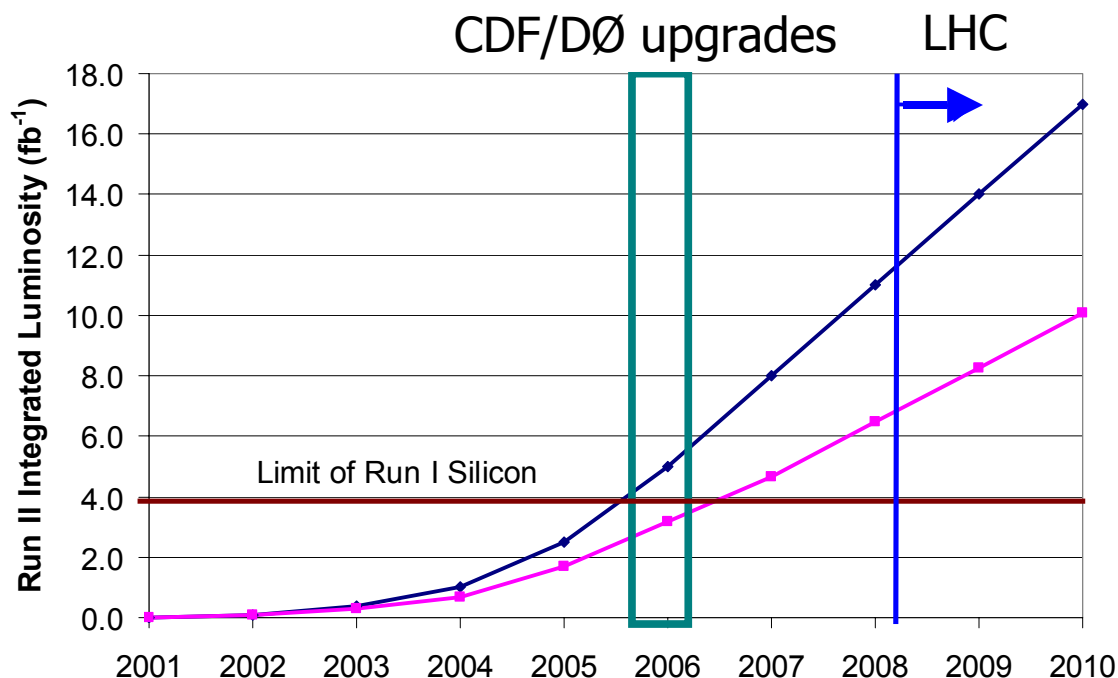


Short term prospects

- For the spring conferences, we plan to “rediscover” the top quark, and present other improved results with $\sim 50\text{pb}^{-1}$
- By next summer’s international conferences, we expect physics results from Run II with $\sim 200\text{pb}^{-1}$
 - significantly increased sample over Run I with improved detectors and a higher center of mass energy
 - Top quark measurements with increased statistics and purity
 - Cross section is 35% higher
 - Silicon b-tagging capability
 - Increased statistics W and Z samples, multiboson samples
 - Start to explore the B sector
 - Jet cross section at high E_T
 - constrain the gluon PDF
 - New limits on physics beyond the Standard Model
 - e.g. MSSM A/H at large $\tan\beta$
 - ...



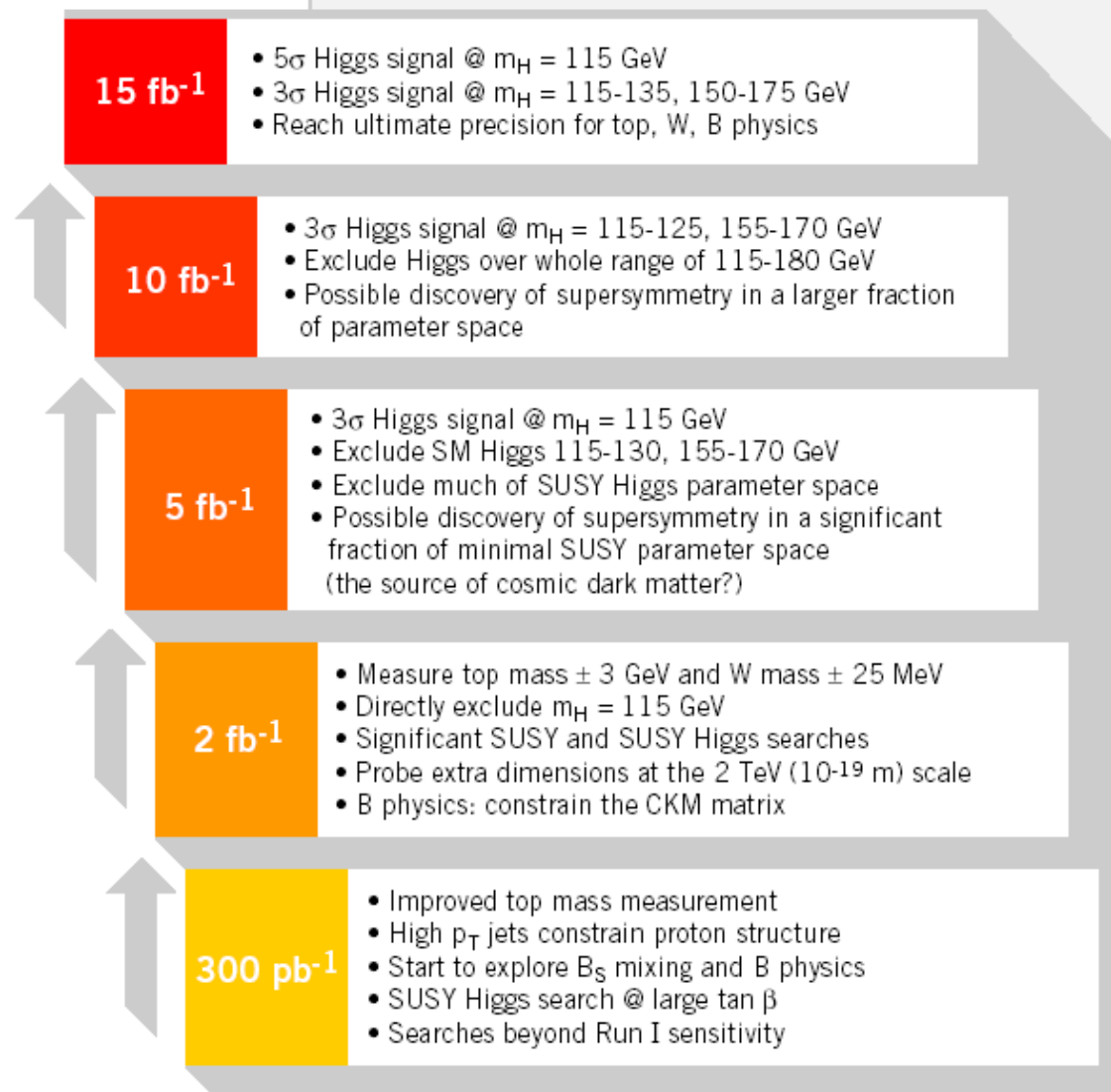
The longer term future



- To realize the full potential of Run II we must continue to upgrade and invest in the detectors and the accelerator
- We will run CDF and DØ until the LHC experiments start to produce competitive physics results
 - The experiments, and the laboratory director, believe we should be prepared to run until the end of the decade



Run II Physics Program



Conclusions

- The Tevatron Collider at Fermilab is the world's highest energy accelerator
- In studying high energy collisions between the fundamental constituents of matter, we are not just trying to understand these constituents, we are trying to address big questions about the universe
 - For example
 - What is the cosmic dark matter?
 - Is the universe filled with energy?
 - What is the structure of spacetime?
- This physics program is based on the detailed understanding of Standard Model particles and forces that we have obtained over the last few decades
 - we are guided by theory but also open to the unexpected
- It's fun!

